

Digital instrument for measurement of aural acoustic immittance: A preliminary report

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Abstract—Development of techniques for measurement of aural acoustic immittance (AAI) is reviewed. Measurement characteristics of selected AAI instruments are compared. Real-ear data obtained with a digital instrument are presented. Review of data support the suggestion that digital AAI instruments promote development of quantitative measurement protocols with greater efficiency and power.

INTRODUCTION

Clinical evaluation of the human middle ear includes measurement of aural acoustic immittance (AAI). Note that immittance refers to impedance (Z) or its reciprocal, admittance (Y). "Aural" indicates measurement in the human ear canal represented by the subscript "a" (Z_a , Y_a) (13). This noninvasive procedure involves presentation of a "probe" tone, usually 226 Hz, to the ear through a probe tube sealed hermetically into the opening of the ear canal. Probe tone level is expressed as an acoustic immittance quantity. (Note that throughout this paper, the *immittance* quantity is *admittance* unless stated otherwise.) Acoustic immittance in the plane of the probe tip affects probe tone level, allowing measurement by the acoustic-immittance instrument. Two clinical measures of aural acoustic immittance are tympanometry and the acoustic reflex response. In tympanometry, a record of AAI ("tympanogram"), obtained as air pressure in the

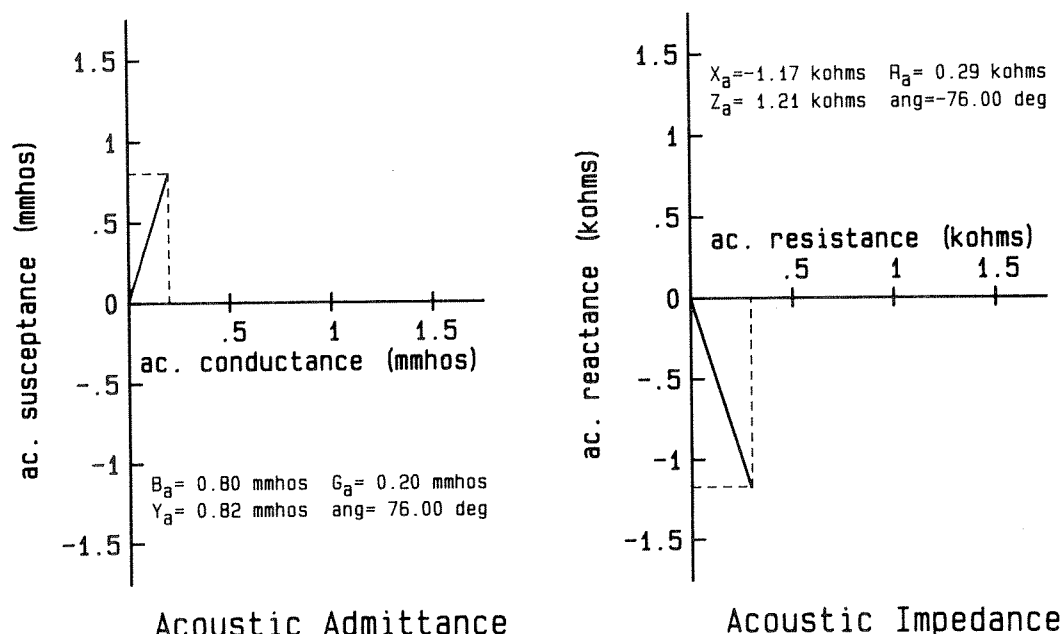
ear canal, varies systematically above and below ambient air pressure. [Air pressure systems in aural acoustic-immittance instruments have ranges as wide as -600 to $+400$ dekapascals (daPa). The pascal is the SI pressure unit (11); $1.0 \text{ daPa} = 1.02 \text{ mm H}_2\text{O}$.]

Estimates of the magnitude of AAI and of the air pressure in the middle ear are commonly derived from the tympanogram. Comparison of these estimates to normative values aid identification of abnormal middle ear conditions. The acoustic reflex response is a record of AAI as the muscles in the middle ear are contracted by presenting relatively intense acoustic, or certain non-acoustic signals, to either ear. (The middle ear or "acoustic" muscle reflex to sound is bilateral. This allows monitoring of muscle contraction in one ear during the time a stimulus or "activator" is presented to the other ear.) Stapedius muscle contraction stiffens the middle ear system, decreasing the admittance of the ear. Absence of the acoustic-reflex response, the signal level required to elicit a threshold response as a function of signal spectrum, and the morphology of the response are useful in diagnosis of pathologies that affect the middle ear and portions of the seventh and eighth cranial nerves, and in objective prediction of presence or amount of hearing loss. As a result, measurement of AAI is a routine component of hearing evaluations.

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* "Technical Notes" are published in the *Journal* as a means of exchanging information concerning an investigator's use of a particular scientific instrumentation or procedure, which might further the course of research. While these original notes are subject to peer review and represent an important contribution to the research literature, they lack controlled comparison studies and are thus different from "scientific articles."

**FIGURE 1**

Vector relationships for aural acoustic immittance. *Right panel:* acoustic impedance (Z_a), the complex sum of acoustic reactance ($X_a = X_{am} - X_{as}$) and acoustic resistance (R_a). *Left panel:* acoustic admittance (Y_a), the complex sum of acoustic susceptance ($B_a = B_{as} - B_{am}$) and acoustic conductance (C_a).

PRINCIPLES OF AURAL ACOUSTIC IMMITTANCE

Adequate descriptions or derivations of acoustic impedance and admittance have been outlined elsewhere [e.g., (8,31)]. After a brief review, this discussion is oriented to the measurement of acoustic immittance in the ear.

Acoustic impedance (Z_a) is the vector or complex sum of acoustic reactance (X_a) and acoustic resistance (R_a) (Fig. 1). The unit of measurement is the acoustic ohm ($\text{Pa}\cdot\text{s}/\text{m}^3$). Acoustic admittance (Y_a), the reciprocal of impedance, is composed of acoustic susceptance (B_a) and acoustic conductance (G_a). The unit of measurement is the acoustic mho ($\text{m}^3/\text{Pa}\cdot\text{s}$). ["Siemen" is the term for admittance in SI units (11); 10.0 acoustic nanoSiemens (nS) = 1.0 acoustic millimho (mmho).] Admittance quantities are shown (Fig. 1) along with the mathematical relationships between them and impedance.

The middle ear system (tympanic membrane and ossicular chain) partially matches the characteristic immittance of air in the ear canal to the input immittance of the cochlea (see ref. 39). Acoustic immittance measured at the probe tip in an ear canal is composed of the immittance of air in the canal between probe tip and tympanic membrane, the immittance of the middle ear, and the transformed input immittance of the cochlea. The latter term is essentially resistive and represents the

cochlear input immittance divided by the middle ear pressure gain. Measures of aural acoustic immittance, a combination of middle ear immittance and transformed cochlear immittance, must be corrected to the plane of the tympanic membrane by removing the immittance of the air in the ear canal.

An estimate of acoustic immittance of air in the ear canal is obtained by measuring immittance at the entrance to the canal as the tympanic membrane is stiffened by reducing ear canal air pressure to at least -400 daPa (28). The admittance at the tympanic membrane is then small with respect to the admittance of air in the ear canal, making the admittance measured at the probe tip relatively free of the influence of the middle ear (13, 25). Correction to the plane of the tympanic membrane for acoustic admittance at low frequencies (e.g., 226 Hz) is

$$Y_{tm} = Y_{probe} - Y_{ec} \quad [1]$$

where Y_{tm} , Y_{probe} , and Y_{ec} are admittances at the tympanic membrane, at the probe tip, and of air in the ear canal between probe tip and tympanic membrane, respectively (31). The correction for acoustic impedance, because the impedances of the air and at the tympanic membrane are in parallel, is

$$Z_{tm} = (Z_{ec} * Z_{probe}) / (Z_{ec} + Z_{probe}) \quad [2]$$

where Z_{tm} , Z_{canal} , and Z_{probe} are impedances at the

tympanic membrane, of the air in the ear canal, and at the probe tip, respectively (14). Presently, it is not possible to separate the middle ear immittance from the transformed cochlear immittance. However, this is not a serious problem, since the middle ear immittance dominates measures made in the ear canal.

Aural acoustic immittance is frequency dependent. The frequency at which impedance is minimum, or admittance maximum, is the resonance frequency (f_0) about 675 Hz in normal middle ears (5). At this frequency, the immittance is composed mostly of the nonreactive component and energy flow is maximum. The middle ear system is stiffness reactance-dominated for frequencies below f_0 and mass reactance-dominated for frequencies above f_0 . Therefore, for the most common probe-tone frequency, 226 Hz, the immittance of a normal middle ear is stiffness reactance-dominated. For higher frequency probe tones, and in the presence of certain middle ear pathologies, the mass reactance of the middle ear becomes increasingly significant, and accurate immittance measurement requires an instrument capable of measuring complex immittance. The reader is referred to Popelka (23) for a recent review of clinical measurement of aural acoustic immittance.

EVOLUTION OF MEASUREMENT TECHNIQUES

Early measurements of acoustic immittance of the ear were made with a mechanoacoustic bridge (19) which was essentially an acoustic analog of the Wheatstone bridge. This device was modified by Zwislocki (37, 38) for measurement of aural acoustic resistance and reactance with probe tones through about 1500 Hz, and produced by Grason-Stadler Corporation as the "Zwislocki acoustic bridge." The instrument was a valuable research tool, providing some of the first reliable estimates of acoustic impedance in both normal and pathological ears (41). Clinical use of the instrument was precluded by the excessive time required for obtaining measures and certain procedural limitations (40). Later methods were based on probe-tube systems (20, 35, 36), consisting of two electroacoustic transducers terminated by short tubes inserted through an earmold. This "probe assembly" was sealed securely in the ear canal. One transducer (speaker or "driver") emitted a low-frequency tone that was monitored with the other transducer (microphone). Sound pressure level produced by a speaker in the ear canal is directly proportional to the impedance of the ear ($Z_{ec} + Z_{tm}$) and analogous to the

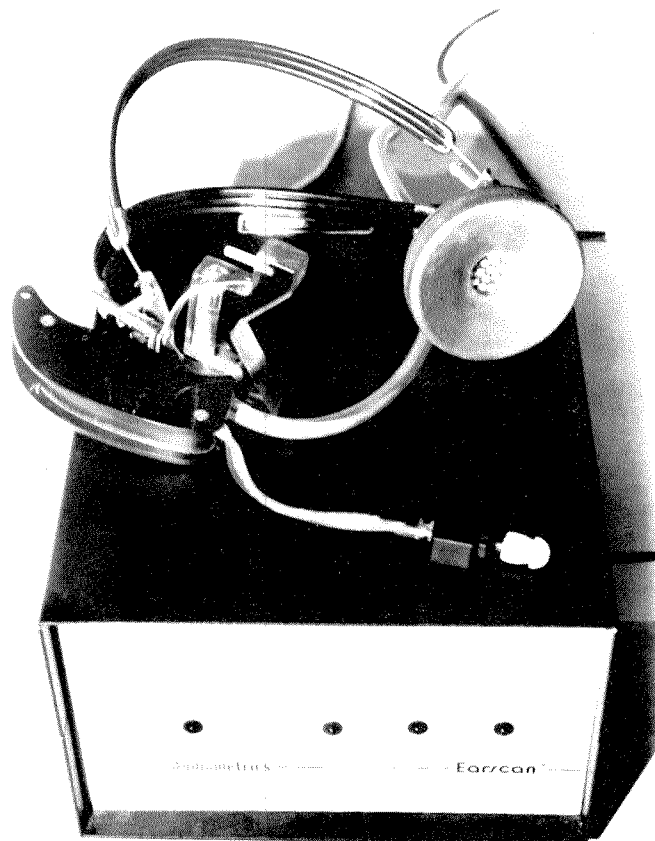


FIGURE 2

Digital instrument (Micro Audiometrics Corp., MA1.1) for measurement of aural acoustic immittance. Probe assembly may be hand-held or mounted on headband.

voltage driving the speaker. Acoustic impedance therefore could be estimated from the speaker driving voltage. Around the same time, a similar probe assembly was developed for measurement of the pressure difference across the eardrum (30). These two systems, used to determine aural acoustic impedance and middle ear pressure, were eventually incorporated into a single assembly with three tubes. The composite system was developed and sold by a number of manufacturers in the late 1960's and 1970's. These instruments were used manually or with analog recording devices for measurement of acoustic immittance in the ear canal, for estimation of air pressure in the middle ear, and for recording the acoustic reflex response.

Several manufacturers have added microprocessors to AAI instruments (1) that perform a select number of "screening" measures more efficiently than analog instruments. However, this advance has not been accompanied by a consistent approach to derivation and computation of basic quantities. Although AAI instruments measure electrical quantities proportional to impedance

or admittance, most instruments convert the measures to other units. One common conversion is to volume (ml^3) of a hard-walled cavity that would yield the same acoustic characteristics (primarily acoustic compliance, C_a), or to units of compliance that air in the cavity would have under standard atmospheric conditions (23). This approach was a logical extension of the use of air-filled, hard-walled cavities for calibration of acoustic-immittance instruments (28). However, there are at least four problems with this measurement unit: 1) some instruments use C_a without an absolute reference, which provides "relative" measures; 2) the magnitude of C_a , which is negligible in a hard-walled cavity, may be significant in ear canal measurements; 3) reporting only one component of the complex immittance results in lost information (40), especially for high-frequency probe tones; and 4) the relative contribution of acoustic compliance to acoustic immittance varies with probe-tone frequency and middle ear pathology. Considerable variance exists among commercial instruments in choice of immittance analogy, use of quantitative units, form and display of the tympanogram, and paradigms for acquisition and display of acoustic reflex responses. Standardization of these features would benefit the current phase of development in aural acoustic immittance, which is an expansion and improvement of measurement procedures.

NEED FOR STANDARDIZED QUANTITATIVE PROTOCOLS

There have been a number of published schemes for measurement, derivation, and calculation of aural acoustic immittance. Clinical applications, however, have been largely qualitative, e.g., association of tympanogram shape with specific middle ear conditions. Several investigators have recommended a more quantitative approach to measurement (7, 17, 21) and, in fact, basic research on measurement procedures has been conducted (e.g., refs. 7, 10, 18, 28). Recent research has shown, for example, that measurement of both components of the complex immittance (6, 32, 33) and the use of probe tones above 226 Hz (16, 27) holds considerable promise for additional clinical applications of tympanometry.

Procedural inconsistencies are especially evident in measurement and application of the acoustic reflex response. There is no standard clinical protocol, although rough estimates of amplitude or adaptation may be obtained in routine audiological evaluations. An efficient approach would include (automated) multiple measures

of acoustic reflex characteristics (e.g., amplitude, latencies, time constants) from single reflex responses (3, 4, 26). This approach has impressive potential for clinical development, but it is not yet supported by the capacities of acoustic immittance instruments. For example, Borg's protocol (2) for measurement of the acoustic reflex's temporal characteristics cannot be accomplished due to the temporal constraints of most instruments (22), or lack of data-processing capability. To complicate the problem, clinicians unaware of instrument limitations may attempt to correct temporal measures of the acoustic reflex with mathematical techniques which, at best, introduce a new source of variance into the data. The role of instrumentation in the development of improved measurement approaches was summed up recently by Silverman, Silman and Miller (29, p. 254), who stated "... further refinement of... techniques such as computer-based digitization of the acoustic impedance... may sensitize... methods... [of analysis of AAI data]."

MERITS OF DIGITAL MEASUREMENT OF AAI

Aural acoustic-immittance (AAI) instruments presently do not provide sufficient support for development or expansion of quantitative measurement procedures. Most instruments measure one component of the complex acoustic immittance, are calibrated in arbitrary units of equivalent volume, and have one probe-tone frequency. At the same time, more complex instruments may require digitization of analog data and automated processing to maintain efficiency. However, this approach is not clinically feasible and does not take advantage of available technology. Presently, the most promising solution is a versatile, digital instrument programmed by an external computer to control all aspects of measurement. Acquisition, storage, and analysis of AAI data, including complex immittance, could be rapid and routine. Adoption and alteration of quantitative procedures could be encouraged through the distribution of software. These considerations, and those discussed earlier (standardized protocols), emphasize the need for AAI instruments that meet stringent design criteria, support the complete array of available acoustic-immittance measures, and are sufficiently flexible to facilitate change in the mode of operation. Presently, the extent to which acoustic-immittance instruments meet such requirements varies considerably among manufacturers (1).

There are at least four major advantages in measuring AAI with a computer-controlled digital instrument:

Measurement. Procedures could be developed to provide the quantitative power necessary for standardization, and automated to reduce operator error and instrument-related sources of variability. Control of data acquisition and processing by host computer software would reduce the responsibility of the operator during data collection so that attention could be focused on data assessment.

Flexibility. Measurement protocols would provide a "menu" selection of test routines, units of measurement, etc. Modification of procedures or incorporation of new standards could be accomplished by upgrading software rather than redesigning entire systems.

User Skill/Training. Control software would be developed by programmers and evaluated by users experienced in AAI measurement. Users of the system would not be required to learn computer programming or a great deal of theory of operation in order to use the AAI instrument effectively. Training could be oriented, therefore, toward clinical applications of quantitative immittance measures.

Cost. A computer-controlled instrument should not require an expensive host computer for control and communication functions. Minimal hardware requirements for the host computer include a standard serial port (9600 baud or higher to minimize data transfer time), at least one disk drive (two facilitate formatting and copying disks), sufficient memory (256 KB) to run applications programs, a monochrome monitor with graphics controller, and a graphics printer. Desirable options include a hard-disk mass storage system, a digital multi-pen plotter, color graphics capability, and additional memory for electronic "disk drive(s)."

An additional benefit of the digital approach is the potential development of standardized quantitative procedures, since calibration and measurement protocols would no longer act as deterrents to improved, more complex, clinical analysis.

IMPLEMENTATION

The digital instrument (Micro Audiometrics Corp. 1.1, "MA1.1") used in the Audiology Research Program is a computer peripheral device that communicates with a host computer (International Business Machines, Personal Computer) via RS-232C serial port. The system supports interactive exchange of operational commands, parameter values, and AAI data. (Extended capability and enhanced performance were added to the MA1.1 as a result of collaboration between the authors and Micro

Audiometrics Corporation.) Simple screening of AAI can be accomplished with a minimum of software development (host computer). The system has the capacity to implement sophisticated data acquisition and analysis.

The MA1.1 is housed in a metal case containing the circuit board, pressure pumps, electromanometer, power supply, and connectors. The probe assembly is housed in a plastic case containing the probe speaker, a speaker for the presentation of acoustic signals for eliciting the ipsilateral acoustic reflex, a connector for the contralateral earphone, and acoustical filtering for the pressure system (Fig. 2). An earphone (Telephonics TDH-39) with cushion (MX-41/AR) is included for the presentation of acoustic signals for eliciting the contralateral acoustic reflex.

Adjustment of air pressure in the ear canal, generation of the probe tone and the acoustic reflex activating signal, and parameters of acoustic immittance measurement are under microprocessor control. Internal programming consists of routines for automatic control/monitor functions and 17 commands called from a host computer. Any of the 128 internal parameter values can be changed under program control. The host computer issues commands, queries the digital AAI instrument on configuration parameters, and transfers data from (or to) the peripheral device.

The digital instrument's monitor program executes the basic functions expected of a general-purpose AAI instrument. The monitor program and calibration constants are loaded from EPROM into RAM at power-up. After initialization of default operation parameters, the program waits for commands from the host computer. The default parameter array includes ± 256 daPa of air pressure for tympanometry, 4.0 cc (equivalent volume) for full-scale range of acoustic immittance, and a 1.0 second duration for acoustic signals used to activate the contralateral acoustic reflex.

The MA1.1 uses an 8-bit microprocessor and both 8- and 12-bit data converters. Measures requiring good resolution and wide range are done with 12-bit converters. Where possible, 8-bit converters are used in conjunction with unique measurement schemes (see discussion of "auto-zero" commands below) to provide sufficient measurement resolution over a restricted range. Data are transferred to the host computer as integer engineering units (EU) which can be converted to immittance, pressure, or time units.

The probe tone is synthesized by 12-bit DA conversion of a stepped waveform (eight sequential steps per cycle at 0, 0.707, 1, 0.707, 0, -0.707, -1, and -0.707 times peak value) followed by low-pass filtering. Probe-tone

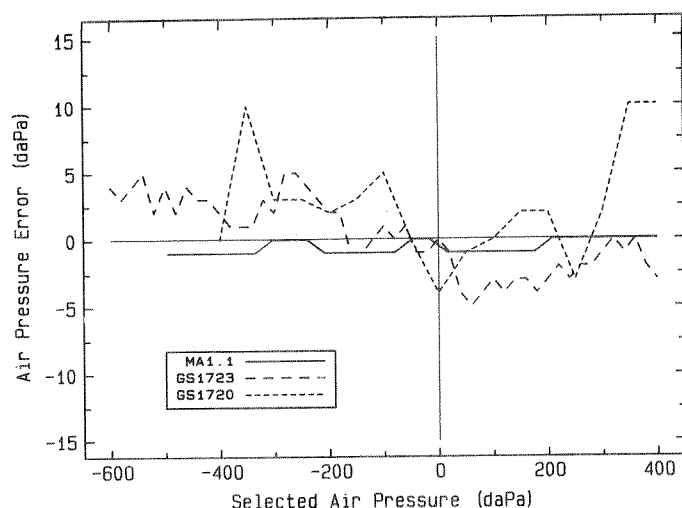


FIGURE 3

Errors in static air pressure measured in coupler for three aural acoustic immittance instruments.

frequency is determined by dividing the probe system clock rate (384 kHz) by a 16-bit parameter value (e.g., 1699 for a 226.015 Hz probe tone). The probe-tone level in the ear canal is maintained by sampling SPL at the probe tip, comparing it to a reference value, and adjusting the driving voltage to the probe speaker to the software-specified reference value, 70 to 85 dB SPL, depending on probe-tone frequency.

The headband adaptor contains a 2-ml hard-walled calibration cavity. The system is calibrated by 1) blocking the probe tip and issuing the "auto-zero magnitude" command, then 2) placing the probe tip in the calibration cavity and issuing a "calibrate-in-cavity" command followed by an "auto-zero angle" command. The "auto-zero magnitude" command references measurements to the probe tip by determining the admittance of the air volume in the probe assembly and subtracting it from subsequent measures. The "calibrate-in-cavity" command performs automatic magnitude calibration by comparing the probe level to that expected for a calibration cavity of a known volume. The MA1.1 measures SPL in the coupler, compares this value to a "correct" value in EU and adjusts a constant to achieve calibration. This process is essentially the digital counterpart of an automatic level control system. The "auto-zero angle" command establishes a reference for phase angle by determining the angle offset that yields 90 degrees in the coupler. The assumption of an exact 90-degree phase shift in the hard-walled coupler introduces an acceptably small error in phase angle measurement in exchange for simple, inexpensive calibration. The instrument then measures shifts in the angle. The actual angle is computed by adding the shifts to the reference angle.

Resolution of angle measurement is programmable from ± 0.053 degrees/EU (± 6.78 degrees) to 1.695 degrees/EU (± 216.97 degrees).

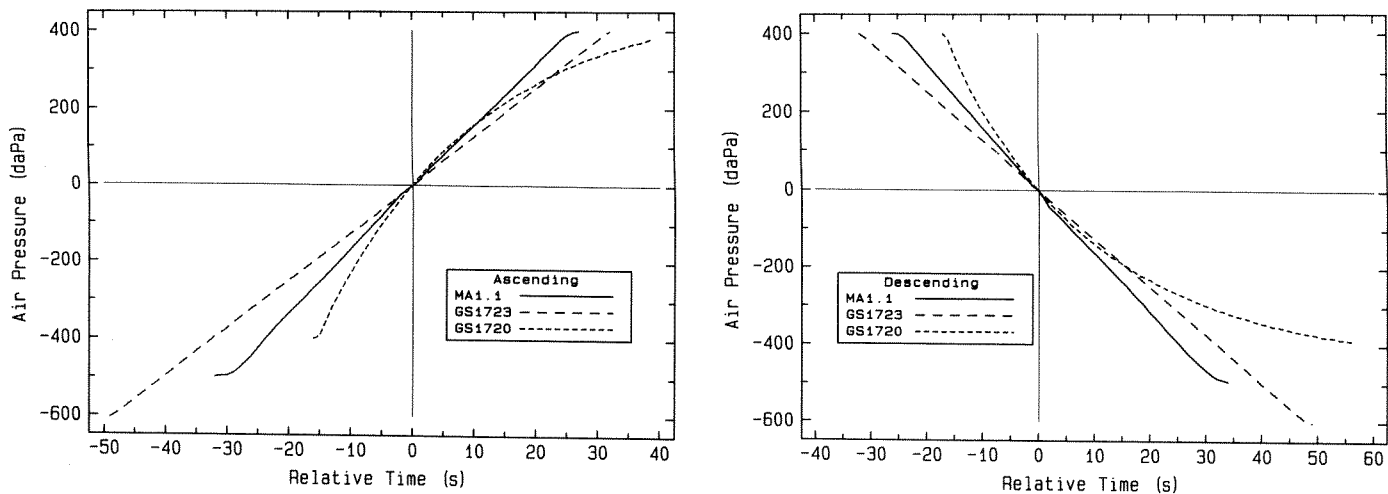
The instrument determines the acoustic-immittance magnitude from the probe driver voltage necessary to maintain the reference SPL in the ear canal. Immittance phase angle is determined by measuring elapsed time between a zero crossing of the synthesized probe tone and a corresponding zero crossing of the acoustic signal measured at the probe tip. The current version of our host computer software converts magnitude and phase angle EU's to Y_a in acoustic millimhos and phase angle in degrees. Acoustic conductance, susceptance, resistance, reactance, and impedance and phase angle then can be computed.

Air pressure is controlled by two pumps. One pump provides positive (greater-than-ambient) and the other negative (less-than-ambient) pressure. The pumps are controlled by a pulse-width modulation system which varies the percentage on-time of the pump power supply. Air pressure in the ear canal is measured with an electro-manometer and delivered to a digitally implemented system analogous to a critically damped analog feedback system. The system can adjust and maintain static values of air pressure or sweep pressure between any two values by changing the appropriate register contents. As with phasor magnitude and angle, host computer software converts pressure values in EU's to daPa. Resolution of pressure setting is programmable from 0.0625 daPa/EU (16 daPa full-scale) to 4.0 daPa/EU (1048 daPa full-scale).

Similar to probe tones, tones for activating the acoustic reflex are generated by DA conversion. Broadband noise is provided by a separate digital generator. Internal calibration is included for contralateral or ipsilateral signal output levels in either SPL or in the hearing threshold level (HTL) for audiometric testing. Calibration constants stored in EPROM are used to "fine-tune" output levels produced by the contralateral earphone in a 6.0 ml coupler (Bruel and Kjaer 4152) and by the ipsilateral earphone in a 2.0 ml coupler (Bruel and Kjaer DB0138). Recalibration or use of a different coupler requires new values to be loaded.

CURRENT STATUS

The MA1.1 requires the extensive development of software for the host computer as well as measurement validation. Major categories of software include transfer of commands and acoustic-immittance data between the

**FIGURE 4**

Dynamic air pressure change for three aural acoustic immittance instruments. Pressure was swept from (left) negative to positive ("ascending") and (right) positive to negative ("descending").

digital instrument and its host, graphic data display, data reduction, data storage, and report format on printer or plotter. Clinical applications require development of software optimized for standard measurement protocols. This software must be user-oriented ("friendly") and menu-driven, so that it can be used with minimal computer experience. Ideally, the software should be fast enough to run in real time so that collection of data, analysis, and reporting can be accomplished within a scheduled clinical evaluation. This requirement will necessitate the use of a programming language that produces compact, efficient, and fast object code. The evaluation of optimal programming strategies and run-time environment is currently underway.

OPERATIONAL ASSESSMENT OF DIGITAL AAI INSTRUMENT

Data from the digital instrument (MA1.1) were compared to data from an analog instrument (Grason-Stadler 1720; "GS1720") used in previous research and a hybrid instrument (Grason-Stadler 1723 Version II; "GS1723-VIIa"; the "a" distinguishes this instrument from a second GS1723-VII used later) which was used for clinical purposes. (It is interesting to note that the GS1720 was the only commercial instrument available in the 1970's for measuring complex acoustic immittance. Although no longer produced by the Grason-Stadler Corporation, many of these instruments are still in use.) "Hybrid" denotes instruments that use a combination of digital switching and conventional analog measurement techniques. Coupler measures of acoustic immittance

and air pressure were compared to predicted values. Real ear measures were made with the digital instrument to illustrate its display and data reduction capabilities.

Air pressure

For static measurements, analog instruments were adjusted manually to static pressures (25.0 daPa increments) indicated by their meters. The digital instrument, or MA1.1, was set to static pressures (32 daPa increments) by command. Pressure range was +400 daPa to -600 daPa (GS1723-VIIa), to -500 daPa (MA1.1), or to -400 daPa (GS1720). Actual pressure was measured in a 2 ml hard-walled coupler (syringe) using an electronic manometer (Setra 339H) interfaced to a computer (Tektronix 4052A) (Fig. 3). Deviations from selected pressure were within ± 1 daPa for the MA1.1, ± 5 daPa for the GS1723-VIIa, and ± 10 daPa for the GS1720. Larger errors for the latter two instruments were expected since discrete pressure settings were achieved by adjusting dials while watching meter displays, both of which introduce additional sources of error into measurements.

Dynamic pressure change also was measured in the 2 ml coupler for the same pressure range. Representative pressure samples were taken from the electronic manometer at the rate of 1/s as pressure was swept in each direction. Results for negative to positive (a) and positive to negative (b) pressure sweeps, respectively, are shown (Fig. 4). Since the three instruments had different pressure limits, average sweep rates were calculated for the range ± 300 daPa. The digital instrument was programmed to use a sweep rate of 16 daPa/s, the

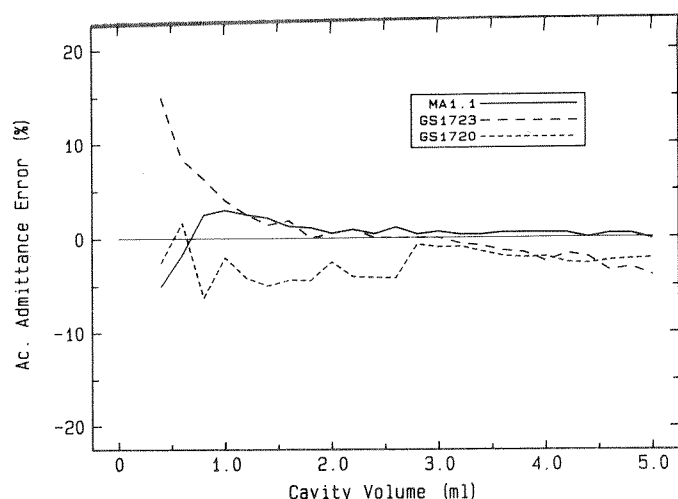


FIGURE 5

Errors in static acoustic immittance measured in coupler for three aural acoustic immittance instruments. Data for MA1.1 were corrected by control software. Data for GS1720 and GS1723 were direct from the instruments.

GS1720 was adjusted to produce a similar rate, and the GS1723-VIIa was set for a "slow" rate of sweep (12.5 daPa/s). Curves in both figures were superimposed at 0 daPa to facilitate comparison among instruments. For the positive to negative sweep (Fig. 4A), the MA1.1 and GS1723-VIIa yielded nearly linear pressure/time functions with slopes of 15.6 and 12.5 daPa/s, respectively. The GS1720 pressure sweep was monotonically decreasing with an overall rate of 16.2 daPa/s. For the positive to negative pressure sweep (Fig. 4B), MA1.1 and GS1723-VIIa functions were approximately linear with slopes of -15.8 and -12.5 daPa/s, respectively, and the GS1720 had a monotonically decreasing function with a rate of -13.6 daPa/s.

Static aural acoustic admittance

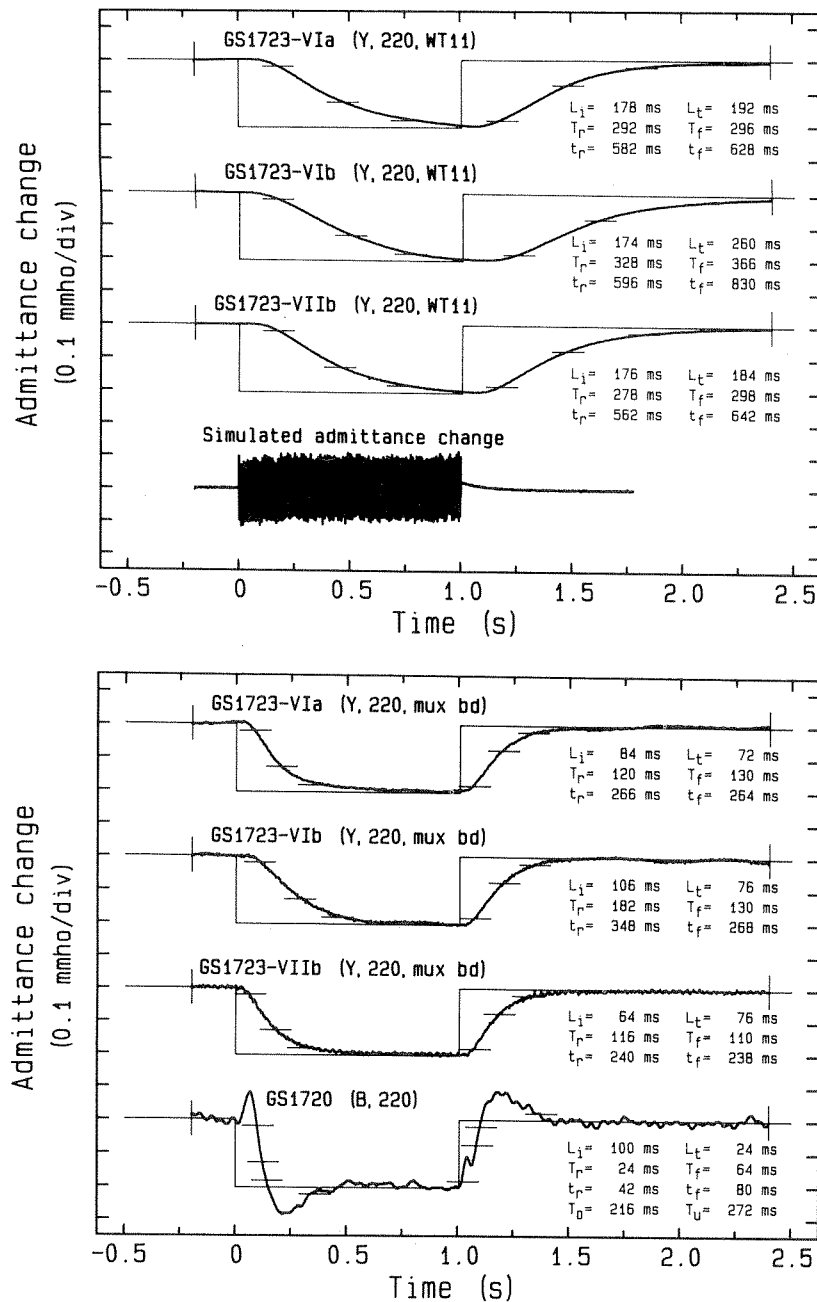
Instruments were calibrated according to specifications using the couplers provided by their manufacturers. Static acoustic admittance measures for each instrument were made in a hard-walled plastic syringe as volume was varied in 0.2 ml steps from 0.4 to 5.0 ml (Fig. 5). The GS1720 and GS1723-VIIa data, taken directly from the instruments, include internal correction for linearity. The MA1.1 data were arithmetically corrected for linearity by the host computer software. A more accurate correction could be obtained by using a correction matrix at the expense of data reduction speed. All three instruments had accuracy within ± 5 percent over cavity volume range from 1.0 to 5.0 ml. Errors tended to be larger below this range. The nominal 5.0 ml calibration

cavity supplied with the GS1720 was actually 5.1 ml, so admittance measures made with this instrument tended to underestimate volumes in the experimental coupler. Post-hoc correction of the MA1.1 data allows individual linearity correction via the host computer for any probe-tone frequency within the range of the instrument (226–678 Hz).

Dynamic aural acoustic admittance

Temporal characteristics of measurement systems were obtained from a GS1720, an MA1.1 and four other instruments: two Grason-Stadler 1723 Version I's (GS1723-VIa and GS1723-VIb), a second Grason-Stadler 1723 Version II (GS1723-VIIb; because the original GS1723 VIIa, was no longer available), and a Micro Audiometrics 1.2 (MA1.2). The latter instrument is the commercial version of our prototype instrument (MA1.1). The two models are functionally equivalent for measurements described in this section.

The measurement technique was similar to that suggested by Popelka and Dubno (15). The probe tip of each instrument was sealed in a plastic syringe (2.0 cc) and was fitted with a microphone (Knowles XL-9073) and a speaker (Bruel and Kjaer HT0003). The signal (probe tone) sampled by the monitor microphone was amplified, attenuated, and delivered to the speaker through an electronic switch (Coulbourn Systems). This allowed generation of a rapid (<1 ms) change in coupler SPL after the switch was triggered, which was adjusted to a level that simulated a change in acoustic admittance of 0.2 ac. mmho. The temporal response of each instrument's measurement system was recorded as "admittance" was decreased from 2.0 to 1.8 ac. mmho for 1 second, then increased to 2.0 ac. mmho. Measurements of the GS1723's (220 Hz probe tone) were taken 1) from pin 6 of U13 on the mux noise board (mux bd; "electrical" response), and 2) from point WT 11 of the meter driver circuit (WT 11; "meter" response). (Temporal characteristics of the GS1723 vary considerably as a function of point in the instrument at which measures are made.) The first measurement point was selected because it is common to both versions of the GS1723 and allows comparison of temporal response differences between Version I and Version II instruments. However, this point follows the AGC and the probe-tone filters in the circuit, yielding longer time constants than would be obtained from points measured "earlier" in the signal path. [It is interesting to note that Grason-Stadler offers an "acoustic reflex latency test" (ARLT) retrofit option which yields shorter time constants (e.g., $\text{Li} = 40$ ms and

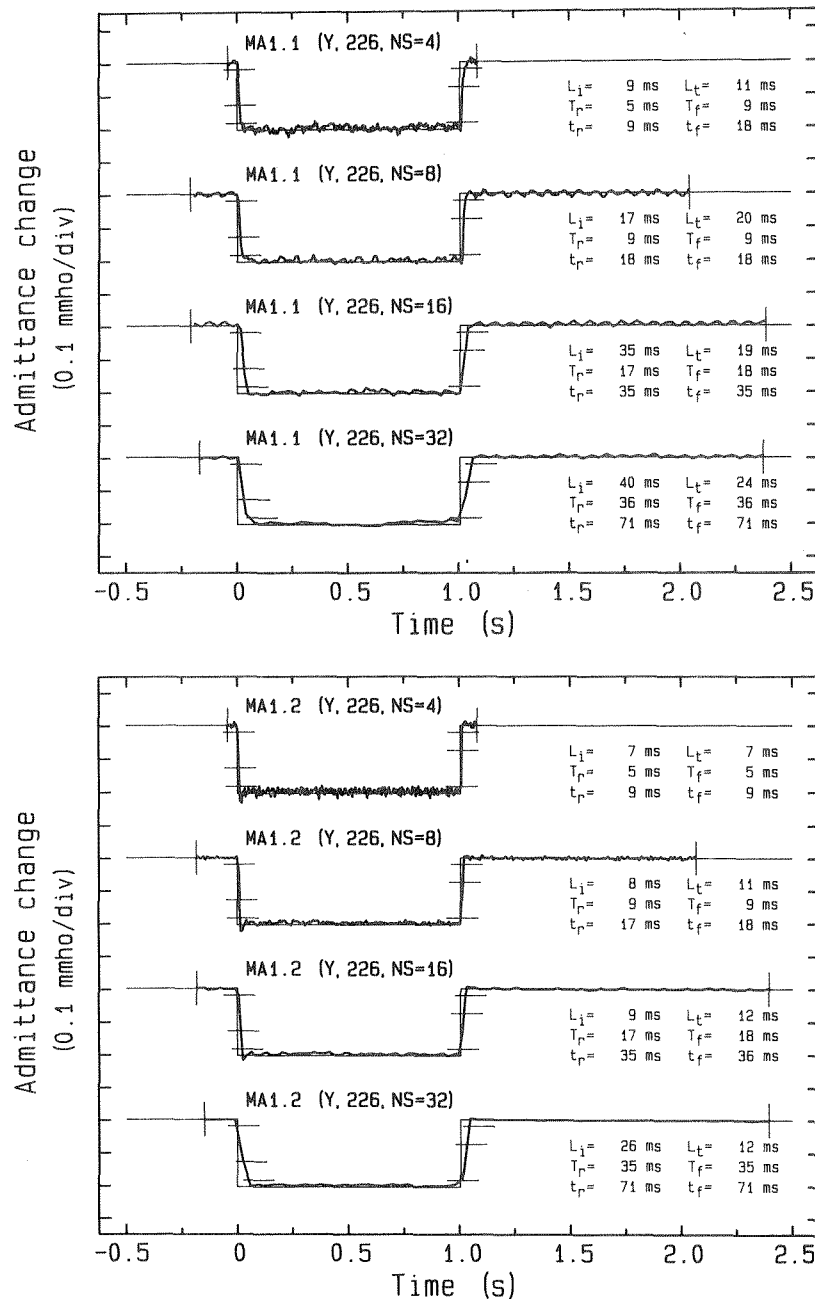
**FIGURE 6**

Temporal responses of four conventional aural acoustic immittance instruments to a simulated change in acoustic admittance of -0.2 ac. mmho for 1 s. *Top and bottom panels are meter responses and electrical responses, respectively. Thin solid lines superimposed on responses indicate change in simulated admittance.*

$t_r = 100$ ms) than those reported (34)]. Measurements of the GS1720 (220 Hz probe tone) were taken from the susceptance output, rectified and low-pass filtered at 20 Hz (Marin Scientific Instruments, custom design).

Responses of the GS1720 and GS1723's to the simulated admittance shift were digitized at 500 samples/s and recorded using a digital oscilloscope (Nicolet 4094). Data from the MA1.1 and MA1.2 (226 Hz probe tone) were obtained from the instruments at sample rates

of 226, 113, 56.5, and 28.2 samples/s ("nsam" register values 4, 8, 16, and 32, respectively). All data, from the digital oscilloscope and the digital AAI instruments, were transmitted to a host computer (IBM-PC) for analysis and plotting. Meter and electrical responses for Grason-Stadler instruments are shown, with the simulated admittance change in the bottom tracing of Figure 6, *top panel*. Temporal responses of MA1.1 and MA1.2 are also shown (Fig. 7). Time course of the

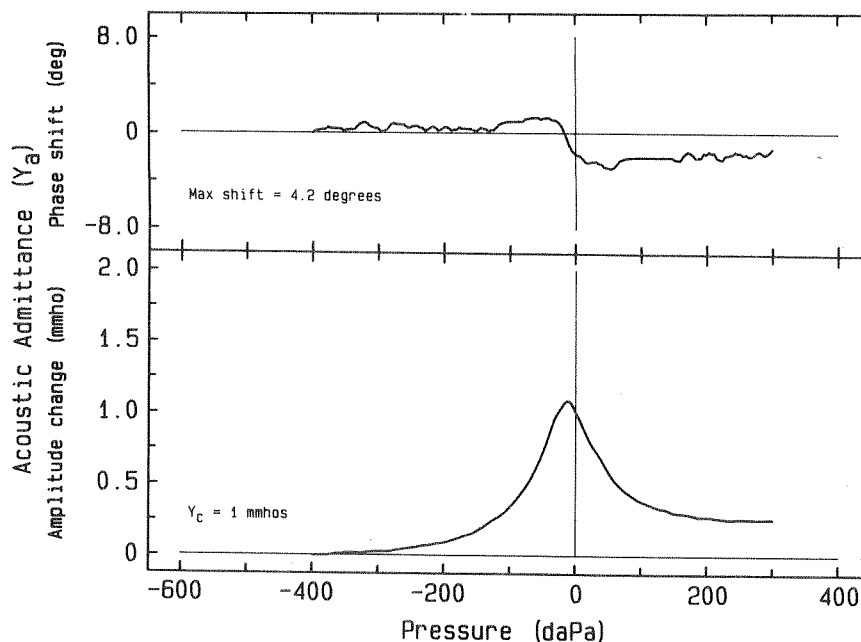
**FIGURE 7**

Temporal responses of two digital aural acoustic immittance instruments to a simulated change in acoustic admittance of -0.2 ac. mmho for 1 s. *Top* and *bottom* panels are for the prototype and commercial versions of the same instrument, respectively. *Thin solid lines* superimposed on responses indicate change in simulated admittance.

simulated admittance change is denoted by thin lines superimposed on all responses.

Temporal responses were quantified using terminology proposed by Lilly (15). Initial latency (L_i), rise time constant (T_r), and rise time (t_r) were taken from the onset of "admittance" change to 10 percent, 63.2 percent, and 90 percent, respectively, of target response. Terminal latency (L_t), fall time constant (T_f), and fall time (t_f) were taken from offset of "admittance" change to 90 percent,

36.8 percent, and 10 percent, respectively, of target response. Horizontal lines mark these measured intervals, with the actual values in ms to the right of each response. Two additional temporal measures were made for one instrument (GS1720) which had overshoots and undershoots greater than 10 percent of target response. Overshoot time (T_o) during onset was taken from 90 percent of target response to recovery to within 110 percent of target response following overshoot. Un-

**FIGURE 8**

Immittance-pressure function and phase angle change measured by a digital aural acoustic immittance instrument. Amplitude was corrected for admittance of air in ear canal. Probe tone frequency was 226 Hz and rate of pressure change was 88 daPa/s.

dershoot time (T_u) during offset was taken from 10 percent of target response to recovery to within -10 percent of baseline following undershoot.

The wide range of sampling rates utilized for data collection, from 2 ms/sample (Grason-Stadler) to 35.398 ms/sample (Micro Audiometrics, $nsam=32$), must be considered when interpreting the data. For the collection of GS1720 and GS1723 data (Fig. 6), timers were adjusted to prestimulus and stimulus intervals within 1 ms and triggered with a push-button switch. Synchronization of the sample epoch with onset and offset of the simulated admittance change therefore was determined by the sample rate of the digital oscilloscope, or ± 2 ms for MA1.1 and MA1.2 (Fig. 7). However, synchronization of the sampling epoch with admittance change was adjusted only for an $nsam$ of 4, and thus became poorer as the number of points averaged ($nsam$) was increased. Readjustment of timers for each " $nsam$ " condition would have improved synchronization without improving accuracy, since corrections were directly proportional to epoch size. As a result, measures of temporal intervals for these instruments were conservative, being overestimated in inverse proportion to sample resolution. The effect is apparent in the shift to the right of the horizontal time markers on responses as the sampling resolution was decreased.

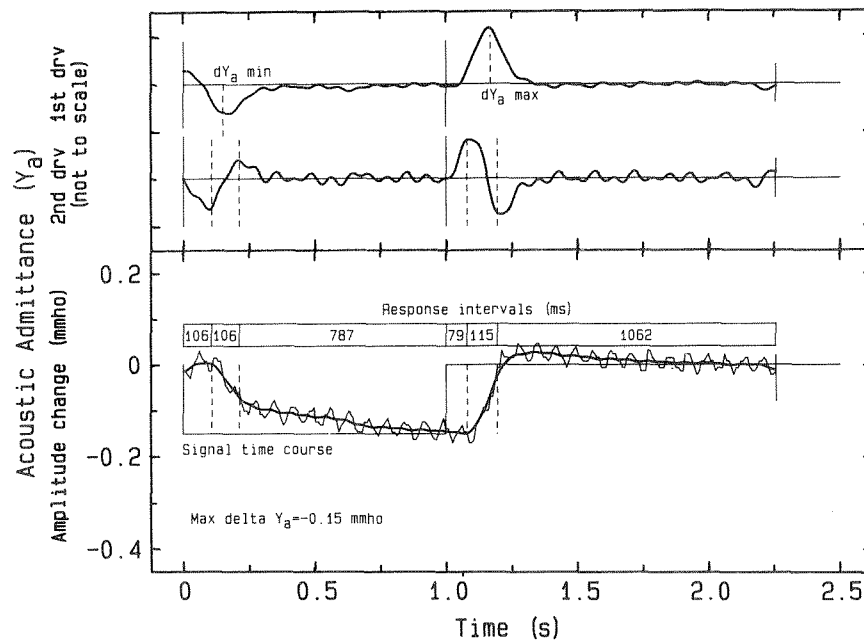
The importance of specifying the point at which measures were made can be seen by comparing "meter"

and "electrical" responses for the GS1723's (Fig. 6). The meter response is considerably slower than the corresponding electrical response. Variations in temporal response also occurred between the two GS1723 versions and, to a lesser extent, between individual instruments of the same version.

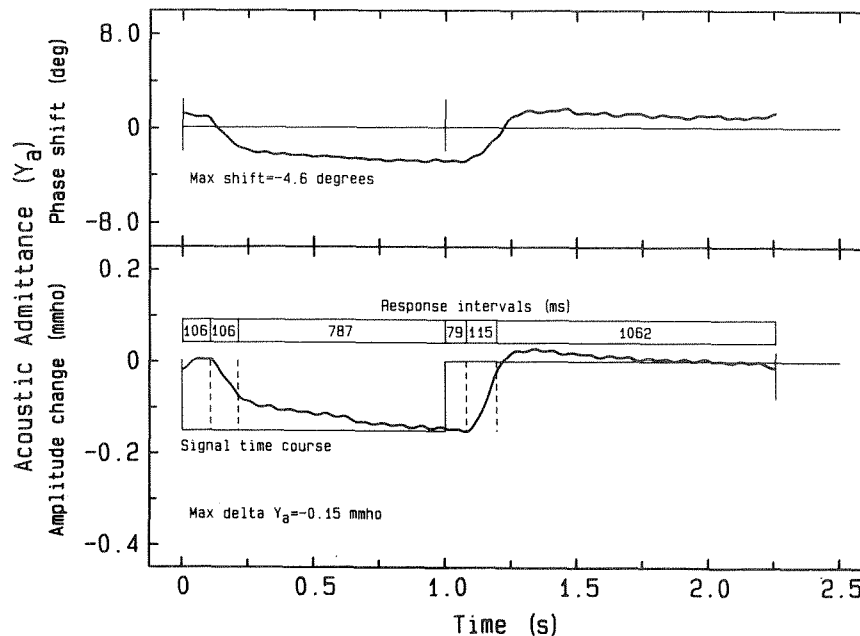
Sample rate, rather than measurement point, must be indicated for MA1.1 and MA1.2 measures, since sample rate is the primary response determinant (Fig. 7). Latencies and time constants can be selected by modifying the sample rate, with the practical restrictions that 1) maximum practical sample rate is one sample per cycle of the probe tone ($nsam=4$), and 2) total sample duration is 256 times the sample epoch. For example, if probe frequency is 226 Hz and $nsam$ is 8, the total sample duration will be 2.26 seconds. Halving resolution will double the total sample time and vice versa.

Tympanometry

An admittance tympanogram was recorded with MA1.1 (226 Hz, 82 dB SPL probe tone) to illustrate concurrent measurement of magnitude (*lower tracing*) and phase (*upper tracing*) (Fig. 8). The tympanogram was initiated by lowering air pressure in the ear canal to -500 daPa and measuring the ear canal admittance amplitude (Y_{ec}) and phase angle (ang_{ec}). These values were stored in the host computer memory and the

**FIGURE 9**

Contralateral acoustic reflex measured with a digital aural acoustic immittance instrument. Amplitude and phase are in *lower* and *upper* traces, respectively. Probe tone was 226 Hz. Reflex activating signal was 1.0 kHz tone presented at 105 dB SPL for 1 s.

**FIGURE 10**

Temporal measurement paradigm for a contralateral acoustic reflex response (*bottom panel*) measured with a digital aural acoustic immittance instrument. First derivative (*upper top panel*) and second derivative (*lower top panel*) traces were computed with host-computer software. Probe tone was 226 Hz.

instrument's phase and amplitude references were "autozeroed" to reference further measures to initial values. Traces in Figure 8 are therefore the change in admittance as a function of ear canal air pressure. (Absolute values could be plotted by adding the offsets determined by MA1.1 to the relative measures.) Pressure was swept

from -500 to $+400$ daPa at a nominal rate of 88 daPa/s, yielding measurement time of about 10 seconds. Since phase and amplitude can be obtained from the MA1.1 in absolute units, admittance tympanograms can be converted to susceptance, conductance or impedance tympanograms (not shown).

Acoustic reflex response

Measurement of the contralateral acoustic reflex with the MA1.1 was preceded by the adjustment of air pressure in the ear canal to the point producing maximum admittance. The paradigm also checked air pressure after reflex response measurement and repeated the measure when the air pressure changed by more than ± 25 daPa. This procedure was adopted to maximize amplitude of reflex responses and minimize reflex thresholds. At this stage of development, reflex responses are subjected to several stages of analysis (26). (Measurement of the ipsilateral acoustic reflex will be addressed in a subsequent study.)

A contralateral acoustic reflex response acquired with the MA1.1 is shown in Figure 9. The reflex activating signal was a 1.0 kHz pure tone presented at 105 dB SPL for 1 second. The time course of the signal (*thin solid line*) is superimposed on the reflex response (*thick solid line*) to illustrate temporal measures. Six temporal response intervals were specified: 1) from signal onset to start of reflex onset; 2) to end of reflex onset; 3) to signal offset; 4) to start of reflex offset; 5) to end of reflex offset; and 6) to end of measurement interval (Fig. 10). The method used to derive the response intervals in Figure 9 is illustrated in Figure 10. The first step was the calculation of ongoing first and second derivative functions and location of the first-derivative minimum (dY_a min) and maximum (dY_a max) points. A temporal search then was made within a restricted range around dY_a min, and the minimum point in the second derivative function preceding dY_a min was defined as the onset of the reflex response. The local maximum in the second derivative function following dY_a min denoted the end of reflex onset. Beginning and end of reflex offsets were determined in a similar manner around dY_a max.

SUMMARY

The aural acoustic immittance (AAI) instrument is used routinely in hearing evaluations by audiologists, otologists, and other health professionals. Development of new clinical applications depends greatly on availability of AAI instruments with greater capacities. The solution is a digital AAI instrument programmed by a

host computer. The digital instrument should have certain minimum capacities: 1) an accurate, well-controlled air pressure system that can vary air pressure in the ear canal from -600 to $+400$ daPa; 2) automated calibration procedures that are simple, efficient, and stable, using inexpensive, easily constructed test cavities; 3) absolute and differential measurement sensitivities sufficient to cover the necessary clinical range; 4) a probe-tone control system that provides accurate adjustment of probe-tone level with short time constants compared to those of the acoustic reflex; 5) selectable probe-tone frequencies from 226 to at least 1200 Hz; and 6) rapid, efficient and flexible data handling. Such an AAI instrument would be capable of meeting stringent measurement requirements with sufficient flexibility to facilitate changes in modes of operation.

One digital AAI instrument (Micro Audiometrics MA1.2) that meets many of these requirements is currently available, and others likely will follow (9, 12, 16). The MA1.2 is a peripheral device attached to a host computer which provides control, communication, and data analysis functions. This system allows automation of acoustic immittance measures which should reduce operator errors, promote appropriate standardization of measurement protocols, and increase reliability. Selection of measurement protocol or adoption of improved quantitative procedures is simplified, since routines, units of measurement, and other variables can be selected via software. Initial laboratory validation of a prototype of this digital instrument has produced promising results.

Utilization of powerful, flexible, digital AAI instruments would promote increased use of quantitative measurement protocols. Adoption of standards would be encouraged and facilitated, since manufacturers could build one basic instrument and provide "levels" of software to meet the levels of standards requirements. These developments should promote research that leads to new clinical applications. ■

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REFERENCES

1. ANONYMOUS: Impedance instrumentation update. *Hearing Instr* 35: 22-25, 1984.
2. BORG E: Dynamic characteristics of intra-aural muscle reflex. In: *Acoustic Impedance and Admittance: The Measurement of Middle Ear Function*, Feldman AS, Wilbur LA (eds.). Baltimore, MD: Williams & Wilkins, 1976, ch 11, pp 236-300.
3. BORG E: Time course of the human acoustic stapedius reflex: A comparison of eight different measures in normal-hearing

- subjects. *Scand Audiol* 11: 237-242, 1982.
4. BORG E, OLDMAN B: Decay and recovery of the acoustic stapedius reflex in humans. *Acta Otolaryngol* 87: 421-428, 1979.
 5. COLLETTI V: Tympanometry from 200 to 2,000 Hz probe tone. *Audiology* 15: 106-119, 1976.
 6. CRETEN WL, VAN CAMP KJ, MAES MA, VANPEPERSTRAETE PM: The diagnostic value of phase-angle tympanograms. *Audiology* 20: 1-14, 1981.
 7. CRETEN WL, VANPEPERSTRAETE PM, VAN CAMP KJ, DOCLO JR: An experimental study on diphasic acoustic reflex patterns in normal ears. *Scand Audiol* 5: 3-8, 1976.
 8. CRETEN WL, VANPEPERSTRAETE PM, VAN CAMP KJ: Impedance and admittance tympanometry. I. Experimental approach. *Audiology* 17: 97-107, 1978.
 9. FUNASAKA S, FUNAI H, KUMAKAWA K: Sweep-frequency tympanometry: Its development and diagnostic value. *Audiology* 23: 99-113, 1984.
 10. HUNG II, DALLOS P: Study of the acoustic reflex in human beings. I. Dynamic characteristics. *J Acoust Soc Am* 52: 1168-1180, 1972.
 11. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION: *SI Units and Recommendations for the Use of Their Multiples and of Certain Other Units*. ISO 1000-1973 (E). New York: American National Standards Institute, 1973.
 12. IVARSSON A, TIERNSTROM O, BYLANDER A, BENNRUP S: High speed tympanometry and ipsilateral middle ear reflex measurements using a computerized impedance meter. Preprint from *Scand Audiol*, 1983.
 13. LILLY DJ: Acoustic impedance at the tympanic membrane. In: *Handbook of Clinical Audiology*, Katz J (ed.). Baltimore, MD: Williams & Wilkins, 1972, ch 23, pp 434-469.
 14. LILLY DJ: Instrumentation for clinical acoustic-impedance measurement. *Impedance Symposium, Mayo Clinic, June 1972*.
 15. LILLY DJ: Evaluation of the response time of acoustic-impedance instruments. In: *The Acoustic Reflex—Scientific Aspects and Clinical Applications*, Silman S (ed.). Orlando, FL: Academic, 1984, ch 4.
 16. LILLY DJ: Multiple frequency, multiple component tympanometry: New approaches to an old diagnostic problem. *Ear Hear* 5: 300-308, 1984.
 17. MANGHAM CA, MILLER JM: A case for further quantification of the stapedius reflex. *Arch Otolaryngol* 105: 593-596, 1979.
 18. MARGOLIS RH, POPELKA GR: Interactions among tympanometric variables. *J Speech Hear Res* 20: 447-462, 1977.
 19. METZ O: The acoustic impedance on normal and pathological ears. *Acta Otolaryngol*, supp. 63, 1946.
 20. MOLLER AR: Improved technique for detailed measurements of the middle ear impedance. *J Acoust Soc Am* 32: 250-257, 1960.
 21. POPELKA GR(ed.): *Hearing Assessment with Acoustic Reflex*. New York: Grune & Stratton, 1981.
 22. POPELKA GR: Instrumentation and procedures for measuring acoustic-reflex thresholds. In: *Hearing Assessment with Acoustic Reflex*, Popelka GR (ed.). New York: Grune & Stratton, 1981, ch 4, pp 47-58.
 23. POPELKA GR: Acoustic immittance measures: terminology and instrumentation. *Ear Hear* 5: 262-267, 1984.
 24. POPELKA GR, DUBNO JR: Comments on the acoustic-reflex response for bone-conducted signals. *Acta Otolaryngol* 86: 64-70, 1978.
 25. RABINOWITZ W: Measurement of the acoustic input immittance of the human ear. *J Acoust Soc Am* 70: 1025-1035, 1981.
 26. ROBINETTE LN, THOMPSON DJ, NALTY DF: Digital measurement of acoustic reflex response in normally hearing subjects. *J Acoust Soc Am* 75: S11(A), 1984.
 27. SHANKS JE: Tympanometry. *Ear Hear* 5: 268-280, 1984.
 28. SHANKS JE, LILLY DJ: An evaluation of tympanometric estimates of ear canal volume. *J Speech Hearing Res* 24: 557-566, 1981.
 29. SILVERMAN CA, SILMAN S, MILLER MH: The acoustic reflex threshold in aging ears. *J Acoust Soc Am* 73: 248-255, 1983.
 30. TERKILDSEN K, THOMSEN KH: The influence of pressure variations on the impedance of the human eardrum. *J Laryng Otol* 73: 409-418, 1959.
 31. VAN CAMP KJ, CRETEN WL: Principles of acoustic impedance and admittance. In: *Acoustic Impedance and Admittance—The Measurement of Middle Ear Function*, Feldman AS, Wilber LA (eds.). Baltimore, MD: Williams & Wilkins, 1976, ch 12, pp 300-335.
 32. VAN CAMP KJ, CRETEN WL, VANPEPERSTRAETE PM, VAN DE HEYNING PH: Tympanometry—Detection of middle ear pathologies. *Acta Oto-Rhino-Laryngologica*, (Belgium) 34: 574-583, 1980.
 33. VAN DE HEYNING PH, CRETEN WL, VAN CAMP KJ, VANPEPERSTRAETE PM: Normative data for two component tympanometry. *Scand Audiol*, 1982.
 34. VEILLETTE R: Personal Communication, Mar. 1985.
 35. ZWISLOCKI J: Some impedance measurements on normal and pathological ears. *J Acoust Soc Am* 29: 1312-1317, 1957.
 36. ZWISLOCKI J: Some measurements of the impedance at the eardrum. *J Acoust Soc Am* 29: 349-356, 1957.
 37. ZWISLOCKI J: Acoustic measurement of the middle ear function. *Ann Otol Rhinol Laryngol* 70: 599-607, 1961.
 38. ZWISLOCKI J: An acoustic method for clinical examination of the ear. *J Speech Hearing Res* 6: 303-314, 1963.
 39. ZWISLOCKI J: The role of the external and middle ear in sound transmission. In: *The Nervous System. Human Communication and Its Disorders*, Eagles EL (ed.). New York: Raven Press, 1975, vol. 3, pp 45-57.
 40. ZWISLOCKI J: Normal function of the middle ear and its measurement. *Audiology* 21: 4-14, 1982.
 41. ZWISLOCKI J, FELDMAN AS: Acoustic impedance of pathological ears. *Asha Monogr* 15, 1970.